

## Research paper

## Regional variations in potential groundwater recharge from spring barley crop fields in the UK under projected climate change

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## ABSTRACT

This study assessed the variations in the impacts of climate change on potential groundwater recharge from barley crop fields in fourteen UK administrative regions. Future climate data, based on the high, medium and low emissions scenarios (or HES, MES, and LES, respectively), were obtained from the UK Climate Projections 2009 (UKCP09) using the weather generator embedded therein. These were used, together with soil, field and calibrated data of the barley genotype Westminster, to simulate potential groundwater recharge in barley crop fields for the 2030s, 2040s, and 2050s. The results show significant variations in potential groundwater recharge for the regions and the emissions scenarios but not the time slices. There was no interaction effect between time and emissions scenarios. For all emissions scenarios, time slices and regions, the largest reduction and increase in potential groundwater recharge over baseline values were 38% and 41%, respectively. East Midlands had the largest reductions for all time slices and emissions scenarios while Southwest Scotland, Northwest Scotland, Northern Ireland and Wales had the largest increase in potential recharge over baseline values. Generally, reductions were prevalent in the south and the eastern regions of England. Reductions were also highest under HES and lowest under the LES. In the 2030, the largest reductions were 37 mm (HES), 29 mm (MES), and 16 mm (LES). In the 2050 the largest reductions were 31 mm (HES), 27 mm (MES), and 19 mm (LES). It is concluded that the regional variations in potential recharge in arable crop fields during the spring-summer season can be a useful input in adaptation planning that integrates agriculture and water resources management in response to flood and drought risks, and water-food security needs.

## 1. Introduction

Groundwater constitutes about 30% of the global freshwater resources and about 96% of liquid water (excluding icecaps and glaciers) (Green et al., 2011; UNESCO, 2008). Groundwater contributes significantly to the world's domestic, industrial and agricultural water supplies (Siebert et al., 2010; Giordano, 2009; Holman et al., 2009). For example, globally, groundwater accounts for about 43% of the 1277 km<sup>3</sup> yr<sup>-1</sup> total consumptive irrigation water use, and about 38% of the 301 million ha of land equipped for irrigation (Siebert et al.,

2010). Being an important component of the hydrological cycle, groundwater is recharged naturally or directly through infiltration (entry of water from the soil surface into the subsurface) and subsequent drainage or percolation (further downward movement of infiltrated water from the root zone). Potential groundwater recharge can be considered as the volume or depth of water that drains or percolates from the unsaturated root zone to an underlying aquifer or saturated zone under a given combination of climate and land use/land cover (Scanlon et al., 2006). Such recharge depends, principally, on hydro-meteorological factors (e.g. quantity, intensity and duration of

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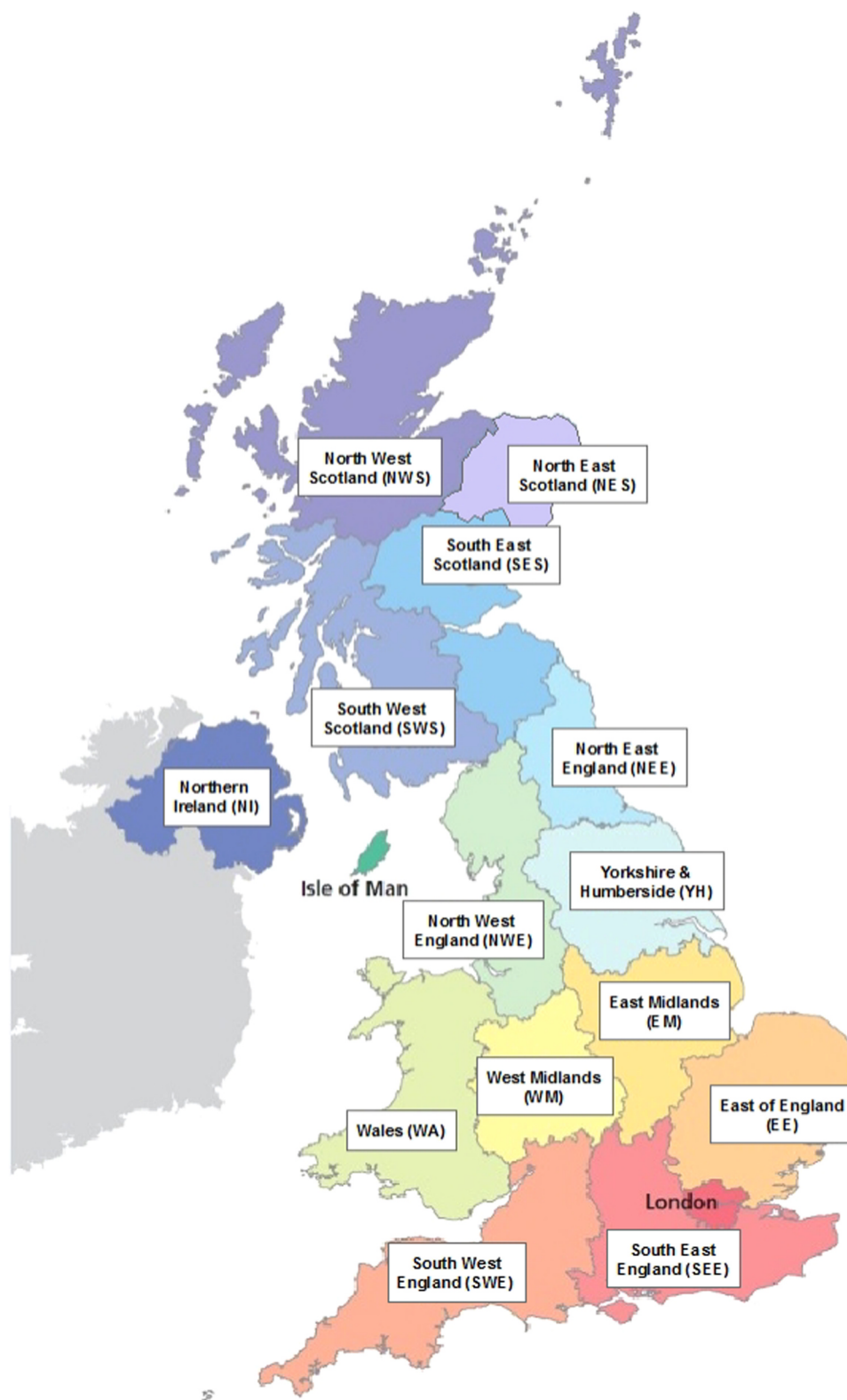


Fig. 1. A map of the fourteen UK administrative regions.

precipitation), hydrogeological conditions of the surface (e.g. geomorphology, geology and pedology), and the land use or cover of the area of interest (Siebert et al., 2010). For the purpose of the current study, potential recharge refers to the depth of water that drains from the unsaturated root zone and can potentially reach the underlying

saturated zone.

Food production and water availability are intricately linked (Yawson et al., 2013; Thenkabail et al., 2010). However, this relationship is often conceived in terms of consumptive use of water for food production, rather than the potential of agriculture to contribute

to water availability. In terms of spatial extent, agriculture is the largest human activity on land (Thenkabail et al., 2010). Through its spatial extent and direct effects on infiltration and percolation, agriculture plays a key role in potential groundwater recharge. Thus, rain-fed crop production contributes to natural, diffuse recharge of groundwater as it plays a role in the quantity, quality and rate of infiltration and percolation through the unsaturated zone to the underlying aquifer. An understanding of this contribution of crop fields to potential groundwater recharge is important for sustainable management of water resources and associated risks. In the context of climate change, estimates and understanding of future contributions of crop fields to potential groundwater recharge would be useful for adaptive responses to climate change impacts on groundwater resources and agronomic management practices such as drainage of crop fields.

Precipitation is the major input to groundwater recharge but this is mediated by the nature of the surface and soil hydraulic properties. Climate change projections suggest, generally, warmer temperatures and increased variability in precipitation (IPCC, 2007). Spatial and temporal shifts, as well as changes in the magnitude of precipitation, will directly affect crop water use, water storage in the root zone and drainage losses from the unsaturated root zone to underlying aquifers. Generally, the impacts of climate change on surface water have been widely studied compared to groundwater recharge, resulting in poor understanding of the impacts of climate change on groundwater recharge globally (Green et al., 2011; Jackson et al., 2011; Holman et al., 2009; Mileham et al., 2008; IPCC, 2007) and in the UK (Jackson et al., 2011). This is due principally to poor availability of data, the complicated and highly variable spatial-temporal responses of groundwater to climate change, and difficulties associated with quantifying groundwater storage (Green et al., 2011; IPCC, 2007). Because it is difficult to accurately quantify the effects of climate change on groundwater storage, studies have largely focused on recharge rates at the catchment scale, with some indicating potentially reduced recharge rates (e.g. Herrera-Pantoja and Hiscock, 2008; Kruger et al., 2001), while others indicate potential increases in recharge rates (e.g. Jyrkama and Sykes, 2007; Kovalevskii, 2007). While the uncertainties of the impacts of climate change on groundwater might be large and pervasive, crop cultivation would certainly affect both direct and diffuse potential recharge of groundwater. Yet, there is little information about future contributions of arable crop fields to potential groundwater recharge across different spatial-temporal scales (Mileham et al., 2008; Green et al., 2011). Further, these contributions are largely neglected in the overall assessments of the effects of climate change on future water resources. The advances in crop-growth simulation models can permit simulation-based assessment of contribution of crop fields to potential groundwater recharge under projected climate change. This, in turn, will permit integration of potential groundwater recharge from crop fields into the assessments of water resources and related management decisions under future climates.

Climate change will likely have varied effects on the contribution to potential groundwater recharge from arable crop fields depending on spatial variability in hydraulic properties and even the distance of the underlying aquifer from the recharge areas (Green et al., 2011). In the UK, there is a heavy reliance on groundwater for domestic, agricultural and industrial uses, especially in England and Wales (Jackson et al., 2011; Hiscock, 2005) and agriculture has the largest share of land use (Defra, 2017). As a result, potential recharge from arable crop fields in the future would be an important factor in the adaptive groundwater and agronomic management responses to climate change in the UK. To this end, the current study aims at contributing to the understanding of potential recharge from crop fields under projected climate change to support such adaptive decisions in the future. The study therefore assessed the variations in potential groundwater recharge from spring barley crop fields in the fourteen UK administrative regions (see Fig. 1) under projected climate change.

## 2. Methods

### 2.1. Data sources

#### 2.1.1. Soil data

Data on soil types, depth and hydraulic properties for the UK were obtained from the New Soil Information System (SINFO) database, which is part of the European Union programme on Monitoring Agriculture with Remote Sensing (MARS) Crop Yield Forecasting System (MCYFS). The scale of the soil data in the SINFO database is 1:1000,000. Detailed description of this database and crop monitoring system can be found in Baruth et al. (2006). Even though there was a 1:250,000 soil data (HOST data) for the UK (which provides a greater spatial detail), it was not freely accessible. In the SINFO database, Europe is divided into Soil Mapping Units (SMU), each comprising a number of Soil Typological Units (STUs) with attributes describing the properties of the soils. In this system, soil texture and bulk density were the main determinants of soil water retention properties which, together with rooting depth, determine the hydraulic properties of the soil groups. The available water capacity (AWC) is defined for each soil group and the product of AWC and rooting depth provides the maximum available water a given soil can supply to a plant. Using ArcGIS version 9.1 (ESRI™, USA), the area covering the UK was clipped and related attribute tables were joined into a single attribute table with all the relevant attributes for the soil polygons representing the UK. Out of the eight main soil texture classes in the database, the UK had five, with the dominant texture class being 'medium'. This national map was intersected with the UK regions to obtain regional distribution of soils and related properties. As soil bulk density and texture were the main determinants of soil water retention properties in the database, the selection of dominant soil class for each region was also based on texture. For each region, the soil class with the largest spatial distribution was selected as the dominant and representative soil class for that region. The weighted averages of the values of the hydraulic properties of the selected soil polygons representing the dominant soil class were used to represent the respective regions. However, where peat was dominant, the next dominant soil class was used. The hydraulic properties obtained from the SINFO database are shown in Table 1.

#### 2.1.2. Climate data

Projected daily climate data were generated for three time slices, 30-year periods centred on the 2030s, 2040s and 2050s, for the fourteen (14) UK administrative regions using the weather generator (WG) embedded in the UK Climate Projections 2009 (UKCP09). The UKCP09

**Table 1**

Soil hydraulic properties obtained from the SINFO database and used in the simulations. Data taken from the SINFO database (Baruth et al., 2006).

Admin. Sub-region	Dominant Soil	θ <sub>sat</sub>	θ <sub>wpw</sub>	θ <sub>fc</sub>	Rooting Depth (m)	θ <sub>asw</sub> (mm/m)
EE	Medium	0.42	0.18	0.33	7	150
EM	Fine	0.49	0.29	0.43	6.8	140
NI	Medium	0.41	0.16	0.31	6.6	150
NEE	Medium	0.42	0.18	0.34	6.6	160
NES	Medium	0.41	0.15	0.30	6.1	150
NWE	Medium	0.43	0.19	0.34	6.4	150
NWS	Medium	0.40	0.15	0.29	7.0	140
SEE	Medium fine	0.55	0.14	0.49	5.9	350
SES	Medium	0.41	0.15	0.32	6.2	170
SWE	Medium fine	0.58	0.15	0.50	4.4	350
SWS	Medium	0.41	0.15	0.31	6.4	160
WA	Medium	0.45	0.22	0.37	6.9	150
WM	Medium	0.45	0.22	0.37	6.7	150
YH	Medium	0.43	0.19	0.35	6.5	160

Note: θ<sub>sat</sub> is saturated water content; θ<sub>wpw</sub> is water content at permanent wilting point; θ<sub>fc</sub> is water content at field capacity; θ<sub>asw</sub> is total available soil water.

is probabilistic and the data are averaged over monthly, seasonal and annual scales (Murphy et al., 2009). However, the WG allows a stochastic generation of statistically credible future climate variables at 5 km resolution on daily or hourly scales from the probabilistic projections (Jones et al., 2009). The future daily datasets were generated under the low, medium and high emissions scenarios (representing the B1, A1B and A1FI, respectively) in the UKCP09. The UKCP09 has been described in detail by Murphy et al. (2009) and the Weather Generator embedded therein has been explained by Jones et al. (2009). For each run of the WG, 100 random data samples were generated from 10,000 variants randomly sampled from the probabilistic projections. The climate data required for the simulations were then extracted from the 100 climate files that resulted from WG request for each region, time slice and emissions scenario. A detailed explanation of the generation and processing of the future climate data can be found in Yawson (2013).

The atmospheric carbon dioxide concentration for the low and medium emissions scenarios and for the three time slices of interest were available in AquaCrop. However, the projected atmospheric carbon dioxide concentration for the high emissions scenario was obtained from the IPCC data distribution centre.

### 2.1.3. Simulations

The AquaCrop model was used to simulate the yield of spring barley crop and water losses beyond the root zone under projected climate change. The simulations were based on the barley genotype Westminster. The AquaCrop model was calibrated for the genotype Westminster using field data obtained under Scottish conditions (see Yawson, 2013), together with information from Raes et al. (2009). According to the Home Grown Cereals Association (HGCA) Recommended List, the genotype Westminster is widely grown in the UK, both as spring and winter barley and is high yielding. The crop parameters used in AquaCrop can be found in Appendix A.

AquaCrop is a crop-water productivity model from the Food and Agriculture Organization. It has been shown to be effective in simulating crop responses to soil water dynamics and climatic conditions. Details of the structure and algorithms of the subcomponents have been reported by Steduto et al. (2009) and Raes et al. (2009). A review of several studies by Steduto et al. (2011) shows that AquaCrop performed satisfactorily in studies on crop water productivity, soil water balance and biomass production. Specifically, the ability of AquaCrop to simulate soil water dynamics has been reported by Andarzian et al. (2011), Patel et al. (2011), Hussein et al. (2011) and Geerts et al. (2009), among others.

The water productivity (WP) parameter is central to crop growth and water use in AquaCrop. The WP is directly related to biomass production. It embodies the intermediary processes of biomass accumulation and is normalized for reference evapotranspiration and atmospheric CO<sub>2</sub> concentration. This normalization makes AquaCrop applicable to different geographic locations, seasons and atmospheric CO<sub>2</sub> concentrations (Raes et al., 2009). Adjustment of the WP parameter for atmospheric CO<sub>2</sub> concentration is done via the equation below (Raes et al., 2009):

$$WP_{adj} = f_{CO_2} \times WP$$

$$f_{CO_2} = (C_i/C_o)/(1 + 0.000138(C_i - C_o))$$

where

$WP_{adj}$  is the adjusted water productivity parameter;  $f_{CO_2}$  is the correction coefficient for CO<sub>2</sub>;  $C_o$  is the reference atmospheric CO<sub>2</sub> (based on observations from Mauna Loa, ppm);  $C_i$  is the atmospheric CO<sub>2</sub> concentration for year  $i$  (ppm)

The WP and crop transpiration control biomass production relative to canopy cover. For unstressed crops, the canopy expands from

emergence to full cover following an exponential growth function; but a decay function is applied from full canopy cover to senescence. The duration between full canopy cover and onset of senescence can vary depending on environmental conditions. Between the minimum and maximum effective rooting depth, root deepening is controlled by a root development shape factor, which is also affected or adjusted by tracking water availability or the water stress parameter. AquaCrop simulates crop water productivity and transpiration responses to elevated CO<sub>2</sub> concentration via an upward adjustment of the water productivity parameter and a downward adjustment of the crop transpiration coefficient based on evidence from FACE experiments (Vanuytrecht and Raes, 2011; Raes et al., 2009).

The soil sub-model of AquaCrop is designed as a dispersed system for which the analyst can specify up to five different horizons (with different textures and depths) for the soil profile. Based on specified soil types and hydraulic characteristics, the soil sub-model calculates the daily water balance in the root zone using an approach which incorporates the processes of runoff, infiltration, redistribution, deep percolation, capillary rise, uptake, surface evaporation and transpiration (Raes et al., 2009). In doing so, AquaCrop separates soil evaporation from transpiration. From input data (mainly saturated water content, field capacity and permanent wilting point), or by specifying the soil textural class, AquaCrop is able to generate the saturated hydraulic conductivity which is used to generate the curve number for the top horizon (Raes et al., 2009). The curve number is adjusted during simulation runs in response to the water content of the top soil. A drainage function, based on the drainage characteristic tau ( $\tau$ ), is used to simulate drainage inside and the percolation out of a soil layer and to simulate the infiltration of water from rain and/or irrigation. The drainage characteristic is proportional to the saturated hydraulic conductivity for the target layer of soil and represents the daily reduction in water content between saturation and field capacity (Raes et al., 2009). AquaCrop uses an exponential equation that incorporates the saturated hydraulic conductivity and soil textural class information of the lowest layer to estimate the maximum possible capillary rise, considering the water content at the bottom of the specified root zone as a driving force (Raes et al., 2009).

In the current study, the climate and soil data, together with the calibration information based on the genotype Westminster were used to simulate the effect of climate change on potential recharge in the fourteen administrative regions of the UK. The simulations were done for rain-fed conditions and fertility stress was not considered. The initial soil water content for each simulation run was set to field capacity and the hydrogeological conditions below the root zone were not considered. Sowing dates ranged from 13th February (for Eastern England, EE) to 24th March (for Northwest Scotland, NWS) and were within the range of the HGCA recommended sowing dates. Harvests occurred between late June and August, with most occurring in July–August. A detailed description of the entire simulation study has been provided in Yawson (2013).

### 2.1.4. Data analysis

For each region, time slice and emissions scenario, the simulation outputs were imported in Microsoft Excel where the 100 output files (resulting from the 100 model variants) were averaged. The total seasonal rainfall and potential recharge data were then extracted and descriptive statistics and charts were generated for these variables. The potential recharge data for each time slice, region and emissions scenario were imported in Stata version 13 where a factorial analysis of variance (ANOVA) with ‘potential recharge’ as the dependent variable was done. Contrast analysis was done for the regions using the Tukey HSD test after detecting significance difference in the model for the regions.

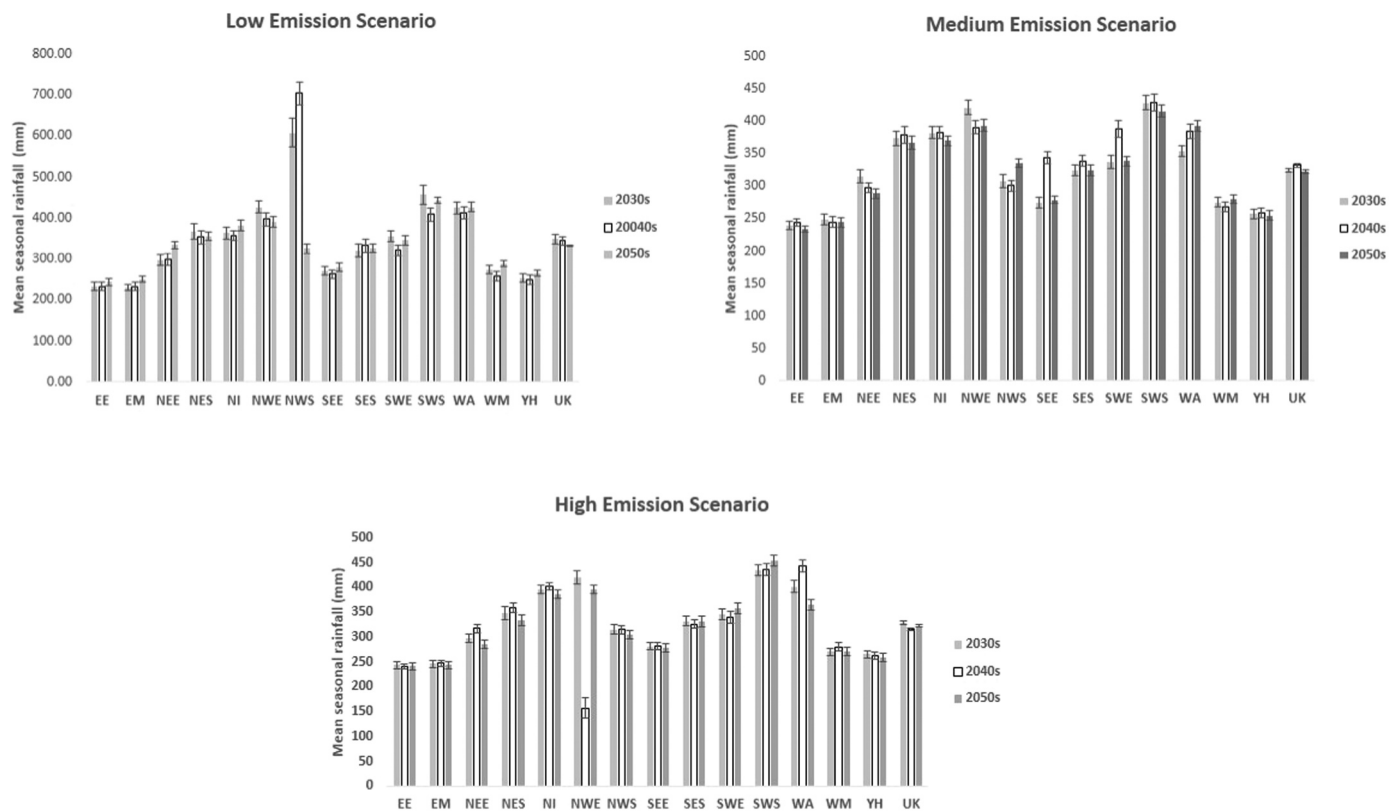


Fig. 2. Seasonal rainfall under the three emission scenarios and the three time slices. Error bars are standard errors.

### 3. Results

#### 3.1. Seasonal rainfall

Generally, the seasonal rainfall for the regions did not vary substantially across the time slices for separate emissions scenarios (Fig. 2). However, differences were observable between emissions scenarios, and for different regions for each emissions scenario. Under the low emissions scenario (LES) and in the 2030s, Eastern England (EE) had the least mean seasonal rainfall (approximately 233 mm) while Northwest Scotland (NWS) had the highest (approximately 608 mm) (Fig. 2). For each region, the seasonal rainfall increased marginally from the 2030s to the 2050s (with few exceptions). Five regions that had the lowest mean seasonal rainfall were EE, EM (East Midlands), SEE (South East England), WM (West Midlands) and YH (Yorkshire and Humber). For the medium emissions scenario (MES), EE had the least seasonal rainfall (240 mm) while Southwest Scotland (SWS) had the highest (429 mm) in the 2030s (Fig. 2). The seasonal rainfall did not vary substantially across the time slices per region. Again, the EE, EM, SEE, WM and YH had low seasonal rainfall. Again, these regions had the least seasonal rainfall under the high emissions scenario (HES) (Fig. 2), with EE recording the least (243 mm) and SWS recording the highest (434 mm) in the 2030s. Apart from Northwest England (NWE) and Wales (WA), seasonal rainfall changed marginally between the time slices.

#### 3.2. Potential groundwater recharge

Potential recharge under the low emissions scenario is shown in Fig. 3. Patterns of increases and decreases over the time slices are observable. For example, the regions that show decreasing trend from the 2030s to the 2050s under the LES include the EE, NES, NWE, SEE, SWE, and YH. The NEE shows an increasing trend while the remaining regions either show a decrease and increase (or vice versa) from the

2030s to the 2050s. Five regions that showed consistently low potential recharge from the 2030s to the 2050s were EE, EM, SEE, WM and YH. The NWS and SWS tended to have the highest potential recharge for the 2030s and 2040s, with the minimum of NWS being higher than most of the other regions. However, in the 2050s, the potential recharge of the regions were comparable apart from the five regions with the least potential recharge. It is also noteworthy that the five regions with the least potential recharge also had very compact box plots, indicating little differences between the third and first quartiles.

For the MES, a similar pattern is observed (Fig. 4). However, decreases in potential recharge are observed for most regions. Particularly, the distinctive high values for NWS and SWS observable under the LES reduce to comparable values with other regions under the MES. However, the EE, EM, SEE, WM and YH remain the regions with least potential recharge across the three time slices, except in the 2040s when there is substantial increase in SEE.

For the HES, a similar pattern of increase and decrease across the time slices were observed (Fig. 5). Only NWE and YH showed consistent decrease from the 2030s to the 2050s while SWS, NWS, and WM showed consistent increases from the 2030s to the 2040s. Under this scenario, Northern Ireland (NI) and Southwest Scotland (SWS) had the highest potential recharge from the 2030s to the 2050s. The same five regions with the lowest potential recharge under the other emission scenarios had the least potential recharge under the HES and they retained their compact box plots.

### 4. Differences between projected and baseline potential recharge

The differences between projected and baseline potential recharge (mean for the period 1981–1990) are presented in Fig. 6. In the 2030s, seven regions (mostly English regions) show decreased recharge over baselines. The largest reductions are observed in EM, SEE, WM, and YH. The NWS shows reductions under the HES and MES and the same pattern is observed for the UK. The largest reduction for all emissions

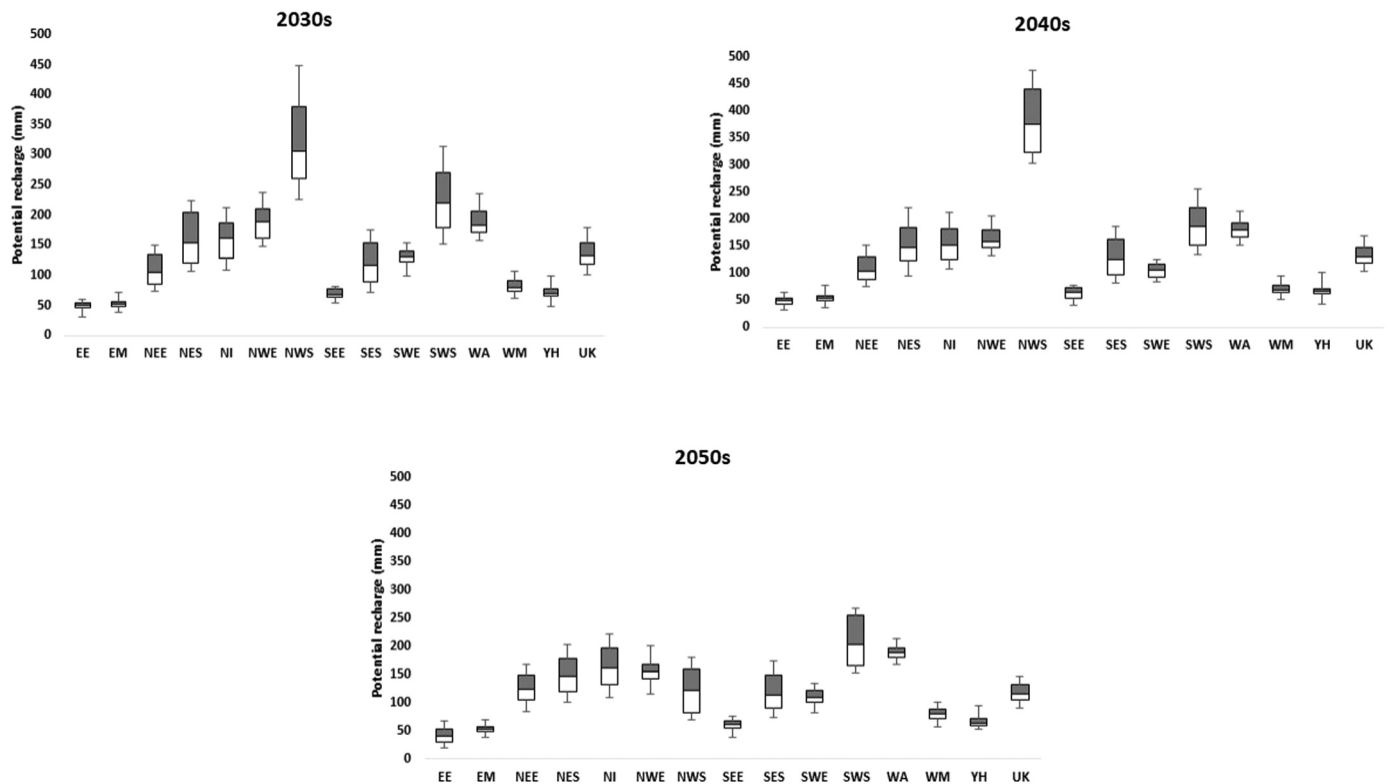


Fig. 3. Seasonal potential recharge under the low emission scenario (LES) for the 2030s, 2040s, and 2050s.

scenarios was 29 mm (YH, MES) and the largest increase was approximately 37 mm (SWS, LES). Similar regional variations in reductions and increases over baseline potential recharge were observed for the 2040s and 2050s, except that the magnitude of the difference changes. In the 2040s, NWS and SES showed the largest increases (approximately 27

and 28 mm) over the baseline values, while WM recorded the largest reductions (up to 38 mm) for all emissions scenarios. Similarly, in the 2050s, WM records the largest reduction under the HES (31 mm) while SWS and WA recorded the largest increase over baseline potential recharge. In all, larger increases in potential recharge across the time

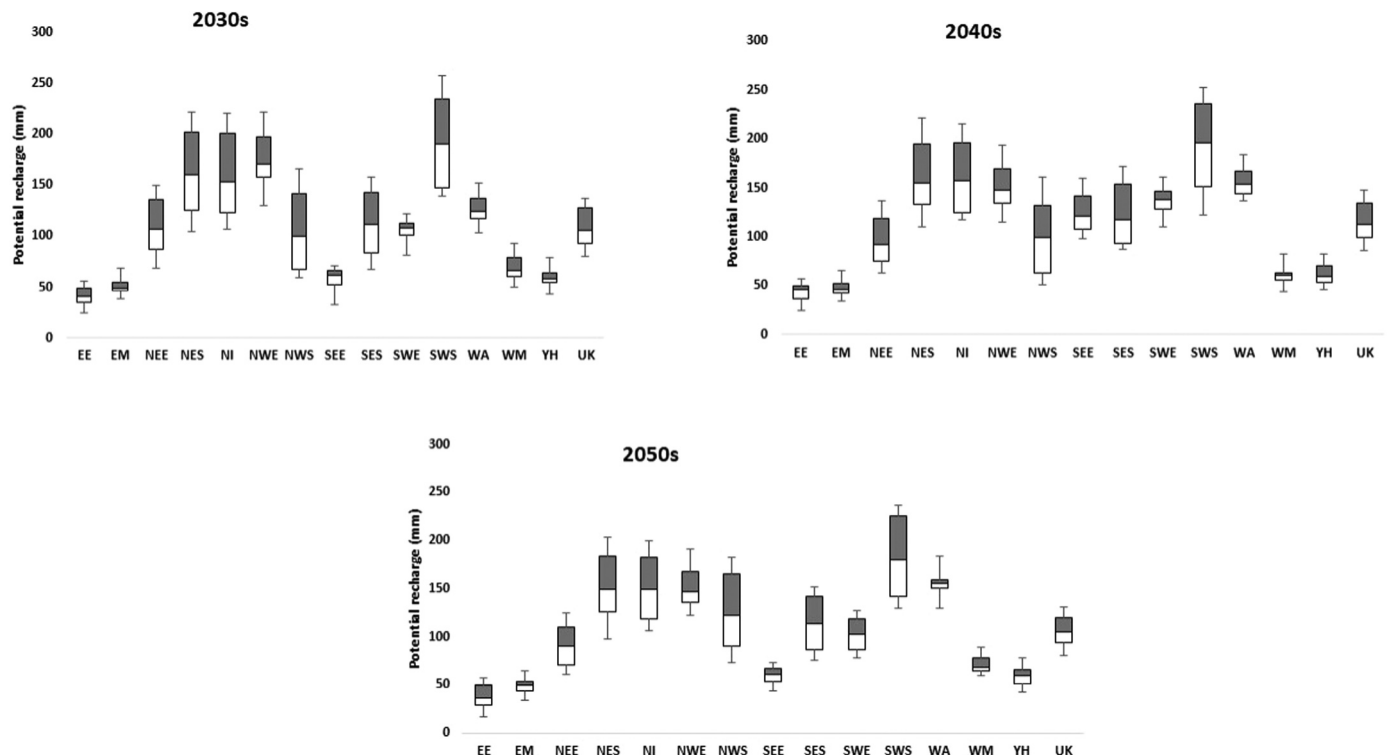


Fig. 4. Seasonal potential recharge under the medium emission scenario (MES) for the 2030s, 2040s, and 2050s.

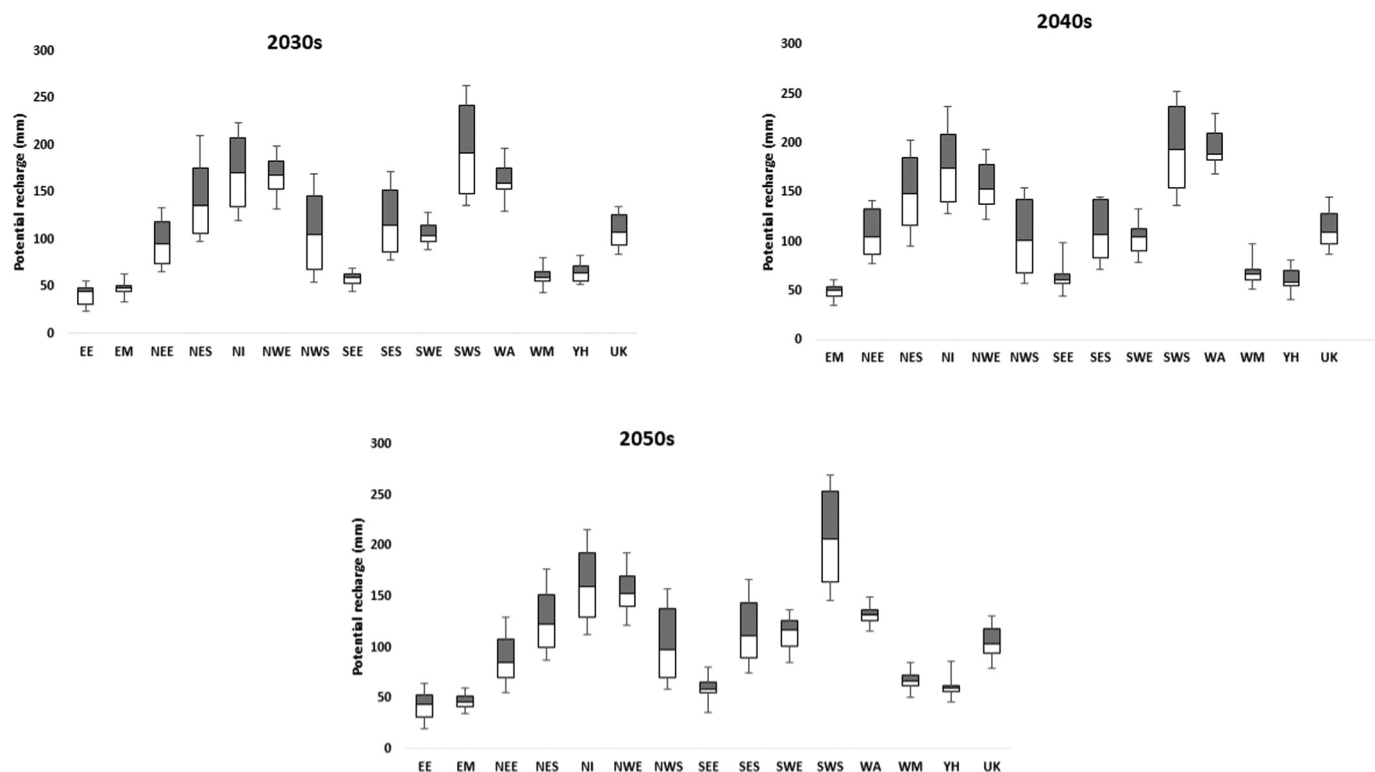


Fig. 5. Seasonal potential recharge under the high emission scenario (HES) for the 2030s, 2040s, and 2050s.

slices were observed under the LES, while the largest reductions were observed under the HES.

The analysis of variance (ANOVA) showed no interaction effect

between time slice and emissions scenarios. The results were invariant between the sequential and partial sums of squares methods. However, the overall model was significant at 95% confidence level (Table 2) as

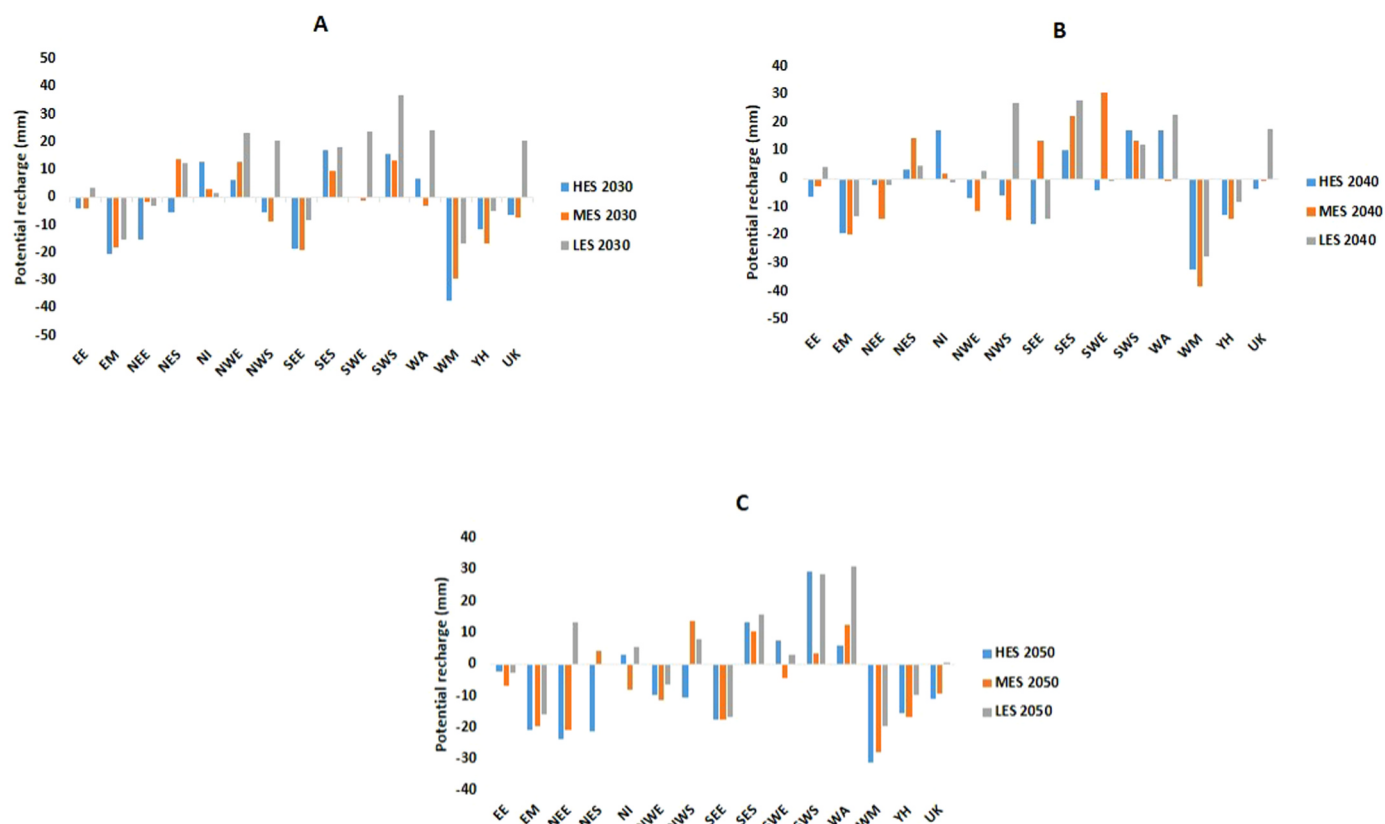


Fig. 6. Differences between projected and baseline potential recharge in the (A) 2030s, (B) 2040s, and (C) 2050s.

**Table 2**  
Analysis of variance of the projected potential recharge.

Source	Seq. SS	df	MS	F	Prob > F
Model	321504	17	18912.019	21.43	0.0000
Emission Scenario	10507.152	2	5253.57598	5.95	0.0035
Time Slice	2893.9752	2	1446.9876	1.64	0.1988
Region	308103.196	13	23700.2458	26.86	0.0000
Residual	95303.302	108	882.437982		
Total	416807.625	125	3334.461		

Number of obs = 126  $R^2 = 0.7713$  RMSE = 29.7059 Adj  $R^2 = 0.7354$ .

the model accounted for over 70% of the variance in the potential recharge. The ANOVA of the potential recharge showed that there were significant differences between emissions scenarios and the regions, but not between the time slices. Because the emissions scenarios had only two degrees of freedom, contrast analysis was done only for the regions (Table 3).

The contrast analysis of the mean potential recharge showed that, across the emissions scenarios, EE was significantly different from NEE, NES, NI, NWE, NWS, SES, SWE, SWS, and WA (Table 2). The EM was significantly different from all other regions except SEE, WM and YH. In addition to earlier observations, the NEE was significantly different from the NI, NWE, NWS, SWS, and WA. Apart from EE and EM, the NES was not significantly different from any other region. Similarly, the NI, NWE and NWS were not significantly different from other regions except EE, EM, and NEE. Overall, the EE and EM were significantly different from nine other regions; the NEE was significantly different from seven other regions; the SWS was significantly different from six other regions while WA was significantly different from five other regions. The SES and SWE were significantly different from four other regions while NES was significantly different from two other regions. The remaining regions were significantly different from three other regions, except WM and YH which were not significantly different from any other region.

## 5. Discussion

### 5.1. Potential recharge in the future

Groundwater remains an important water resource for many countries, including the UK. In the face of climate change, simulation of future trends in potential recharge can support planning and proactive management decisions on groundwater resources (Gemtzi et al., 2017). In the current study, a water-driven model (AquaCrop) was used to simulate potential recharge from spring barley crop fields in the UK under projected climate change, covering the spring-summer season (the period from sowing to harvesting of spring barley). This is important as agriculture covers the largest share of UK land use, with cereals accounting

for the largest share of cultivated crops (Defra, 2017). Projected reductions in summer rainfall and increases in warmer temperatures in the UK are centred on June–July–August (Wilby et al., 2010; Jenkins et al., 2009; Murphy et al., 2009). Herrera-Pantoja and Hiscock (2008) studied the effect of climate change on three UK aquifers and showed that the main effect of climate change on potential recharge was evident in the period April–September. These suggest that an understanding of contribution of crop fields to potential recharge during the spring-summer period would be useful for adaptation planning. The current study therefore highlights potential recharge from crop fields (using spring barley) during the spring-summer season in the future.

Projected changes in precipitation due to climate change have larger uncertainties than temperature (Murphy et al., 2009). In the current study, projected mean seasonal rainfall for spring barley did not show substantial variations across the three time slices for a given emissions scenario but there were much variations between the regions and a tendency towards reduction from the LES to the HES. Mainly, the regions in the eastern half of England had the least seasonal rainfall, except West Midlands (WM) which is in the west, and Northeast England (NEE, Fig. 2). This observation is consistent with the fact that precipitation in the UK increases from east to west (Murphy et al., 2009). Regardless of the low rainfall in these regions, the barley crop was found to potentially remain viable under the projected climate change in all the UK regions studied (Yawson et al., 2016; Yawson, 2013).

The quantity (and distribution) of seasonal rainfall has direct relationship with the quantity of water contributed to potential recharge. Often, groundwater recharge is regarded as the vertical flow of water across the water table even though it can include cross-formational flows from adjacent or underlying hydrogeologic formations (Green et al., 2011). In the current study, the pattern of potential recharge for the regions seems to follow the east-west and south-north gradient in rainfall for the UK, as well as the regional differences in the magnitude of mean seasonal rainfall (Fig. 2). However, because the mean rainfall for the regions did not vary substantially across the time slices, the observed variations in potential recharge across the time slices could be in response to a variable other than rainfall. While potential recharge is expected to correspond to rainfall patterns, it is not always the case. According to Crosbie et al. (2013), studies have shown that increased rainfall intensity, changes in wet/dry spell duration or changes in the time required for annual crops to complete their life cycle might affect variations in potential recharge under different climate change scenario, without a direct relationship with rainfall. Potential recharge is sensitive to both changes in temperature and precipitation (Gemtzi et al., 2017). For example, Gemtzi et al. (2017) showed that a unit change in decadal precipitation resulted in less than 1.5% change in decadal recharge whereas a unit increase in decadal temperature resulted in up to approximately 11% decrease in decadal recharge. They reported that future recharge during winter corresponded to projected winter precipitation

**Table 3**  
Contrast analysis for UK regions (Tukey HSD test at 95% Confidence Level).

	EE	EM	NEE	NES	NI	NWE	NWS	SEE	SES	SWE	SWS	WA	WM	YH
EE														
EM	7.69													
NEE	61.54 *	53.85 *												
NES	109.23 *	101.54 *	47.69											
NI	120.05 *	112.36 *	58.51 *	10.82										
NWE	121.09 *	113.40 *	59.54 *	11.86	1.04									
NWS	121.36 *	113.67 *	59.81 *	12.13	1.31	0.27								
SEE	25.95	18.26	– 35.59	– 83.28	– 94.09	– 95.14	– 95.41							
SES	76.09 *	68.40 *	14.55	– 33.14	– 43.96	– 45.00	– 45.27	50.14 *						
SWE	70.25 *	62.56 *	8.71	– 38.98	– 49.80	– 50.84	– 51.11	44.29	– 5.84					
SWS	156.25 *	148.56 *	94.71 *	47.022	36.20	35.16	34.89	130.30 *	80.16 *	86.01 *				
WA	123.00 *	115.31 *	61.46 *	13.77	2.96	1.91	1.64	97.05 *	46.91	52.76 *	– 33.25			
WM	27.63	19.94	– 33.91	– 81.60	– 92.42	– 93.46	– 93.73–99.72	1.68	– 48.46	– 42.62	– 128.62	– 95.37		
YH	21.64	13.94	– 39.91	– 87.59	– 98.41	– 99.45		– 4.32	– 54.45	– 48.61	– 134.62	– 101.37	– 5.99	

while spring-summer recharge corresponded more with temperature. Crosbie et al. (2013) reported that a 1% change in rainfall resulted in 2% change in recharge for the US High Plains, and reductions in recharge under the warmer scenario was not related to changes in rainfall. This suggests that warming conditions could account for the observed variations in regional potential recharge across the time slices and emissions scenario. This, in turn, suggests that the combination of projected low summer rainfall and warmer temperatures (Murphy et al., 2009) could have grave impacts on potential groundwater recharge or supply at a period when consumptive use of water could be high, especially in the English regions that recorded low potential recharge.

Warmer temperatures operate through evapotranspiration to affect crop growth and potential recharge. In the current study, evapotranspiration, together with the quantity and distribution of rainfall, could account for the observed variations in regional potential recharge (Figs. 3–5). Seasonal crop evapotranspiration (ETc) increased slightly from the 2030s to the 2050s (Appendix B). In addition, the regions that had low potential recharge had corresponding high seasonal ETc. For example, prominent regions with higher seasonal ETc (but low variability in ETc within a time slice and emissions scenario) included EE, EM, SEE, and SWE (Appendix B). In the 2050s, under the HES, ETc of EE was suppressed due to faster phenophases and attainment of total thermal time. In the current study, potential recharge was generally highest under the LES and lowest under the HES, an observation that is consistent with previous studies (Gemitz et al., 2017; Crosbie et al., 2013; Eckhardt and Ulbrich, 2003; Richter and Semenov, 2005) that potential recharge can decrease under warmer conditions even if rainfall does not change substantially. This can be due to low evapotranspiration resulting from moderate increase in temperatures together with adequate rainfall under the LES (Ficklin et al., 2009; Murphy et al., 2009) while higher evapotranspiration rates (Appendix B) would account for the relatively lower potential recharge under the HES. For example, under high evapotranspiration conditions and decreasing soil water content, crops create high matric potential in the root zone, potentially resulting in moderate transport of water downwards (Scanlon et al., 2005; Bölske, 2002).

A study by Eckhardt and Ulbrich (2003) showed that slightly warmer temperatures under the LES caused only minute reductions in groundwater recharge, compared to the HES, in the Dill catchment in Germany. Richter and Semenov (2005) reported that, even under projected increase in precipitation, maximum soil moisture deficit in wheat fields in England and Wales will reduce by about 20 mm due to higher rates of evapotranspiration arising from warmer temperatures. In addition, the average maximum soil water deficit were lower in the west and north compared to the eastern and southern regions. However, they observed that in the 2050s, these differences will narrow as the western regions appeared to be more hydrologically responsive, resulting in larger changes, than in the eastern and southern regions. In the current study, however, the largest reductions for the 2030s were 20 mm (EM) and 37 mm (WM) under the HES; 19 mm (SEE) and 29 mm (WM) under the MES; 15 mm (EM) and 16 mm (WM) under the LES (Fig. 6). In the 2050s, the largest reductions were 23 mm (NEE) and 31 mm (WM) under the HES; 21 mm (NEE) and 27 mm (WM) under the MES; and 16 mm (SEE) and 19 mm (WM) under the LES. The results in the current study therefore compare reasonably well with the results of Richter and Semenov (2005), noting that the latter was based on the A1B (or the MES). Further, in the current study, the reductions in potential recharge rather increases in the southern and eastern regions (e.g. EE, EM, SEE, YH) from the 2030s to the 2050s, and from the LES to the HES, due to the ETc gradient (Appendix B) and soil water depletion which consequently limit potential recharge (Calanca et al., 2006; Scanlon et al., 2005; Arnell, 1998). In the western regions, higher rainfall (Fig. 2) saturated the soils (data not shown; see Yawson et al., 2016) and suppressed ETc, resulting in rather higher potential recharge.

For the UK, we did not find a similar study on potential recharge from crop fields at regional scale to allow robust comparison. There is limited information on the contribution of arable crop fields to future potential

groundwater recharge even though there have been studies in specific catchments. Jackson et al. (2011) studied the impacts of climate change on a Chalk aquifer in south-central England using an ensemble of 13 global climate models run under the A2 (medium-high) emission scenario for the 2080s. The overall ensemble results ranged from a decrease of 26% to an increase of 31% in potential recharge. Ten of the global climate models predicted a decrease while three predicted an increase. Jackson et al. (2011) found little variation in annual recharge but significant variation in seasonal recharge (especially between April and October) and more concentrated recharge during winter. This significant variation in Spring-to-Autumn recharge is important for water resources management and use in relation to potential recharge from arable crop fields, especially in the face of projected low summer rainfall and stream flow (Murphy et al., 2009). In a similar study, Herrera-Pantoja and Hiscock (2008) assessed the potential groundwater recharge on two catchments in south-east England under the HES. They reported 20% reduction in potential groundwater recharge for sites in East Anglia and 40% for sites in Sussex. These two studies used catchment models that employ similar soil water balance sub-model. They both used one time slice and one emission scenario. The largest reduction in potential groundwater recharge in the current study was 38% while the largest increase was approximately 41% for all regions, time slices and emissions scenarios. Thus, the results in the current study compares well with the catchment-based results. The added value in the current study is that it is based on contribution to potential recharge from arable crop fields and multiple regions, time slices and emissions scenarios. Hence, the current results can feed into land use and agricultural land management practices and decisions to influence potential recharge in the future.

Arnell (1998) noted that, in the UK, groundwater is largely recharged by winter precipitation after satisfying soil deficits and before they begin to develop again in spring. While this might suggest that projected increases in winter precipitation (Murphy et al., 2009; Arnell, 2004) will sufficiently increase groundwater recharge, the rate of evaporation can have a controlling effect. Thus, a higher evaporation rate would likely reduce the length of the recharge season and thereby diminish the effect of higher winter rainfall (Arnell, 1998). This, together with projected low summer rainfall and related soil water deficits (Calanca et al., 2006), makes potential spring-summer recharge a crucial supplement to groundwater especially in southern and eastern England. To this end, the contribution from arable crop fields would equally be important, feeding into land use and water management decisions and practices. Results of the current study suggest that the EE, EM, SEE, WM and the YH will have low contribution to potential groundwater recharge from arable crop fields. Another implication is that postharvest soil water deficits in these regions might be high and, thus, further reducing the quantity or increasing the duration of winter recharge. The results of the ANOVA and contrast analysis show that the EE and EM should be particularly watched for these conditions, followed by the NEE and SEE. Conversely, in some regions (e.g. Scottish regions), large additions to groundwater during the spring-summer season, and residual postharvest soil water content prior to winter might be undesirable as this can contribute to flooding. In the current study, the Scottish regions (especially the SWS), Wales and Northern Ireland had relatively larger contributions to potential groundwater recharge. It was also observed in the simulations that these regions frequently suffered from soil saturation (Yawson, 2013). These areas are worthy of monitoring for saturated conditions and potentially, flooding events during high winter precipitation and intense spring-summer rainfall (Arnell, 1998). The results also suggest that agricultural operations (especially those related to tillage) have to be carefully considered and timed in the future as part of adaptation planning in response to potentially excessive soil saturation. The ANOVA and contrast analysis suggest that SWS, NWS, NI, and WA should be given attention for these conditions. These conditions, of course, would also be influenced by the type and hydraulic properties of the soils, their spatial variations and how they are managed.

## 5.2. Implications for water resource management

In the UK, climate change is projected to cause warmer and shorter wetter winters, and hotter and longer drier summers, but the impact of lower summer flows is expected to be greater in England and Wales (Arnell, 2004). The Environment Agency (2010) reported that, by 2050, there could be 50% reduction in river flows during summer due to climate change, and up to 80% in other areas. However, winter flows could increase by about 15% over a shorter period. Water scarcity is already an issue in England and Wales (Charlton and Arnell, 2011; Royal Geographical Society with IBG, 2012) where groundwater contributes substantially to public water supply in urban and rural areas, agriculture, electricity and industrial uses (Hiscock, 2005). Irrigated horticulture (which occurs largely in the driest period – summer) has increased substantially in these two regions for the past two decades (Knox et al., 2010). The Environment Agency recently indicated that only 16% of all horticultural holdings in England and Wales were within catchments where additional abstraction licenses could be possible during summer low flows, 59% were within over-licensed (water-stressed) catchments, and 20% were within over-abstracted (water-scarce) catchments, while 35% of holdings irrigated by mains water were within zones which were seriously water-stressed. Charlton and Arnell (2011) assessed the 25-year Water Resources Management Plans (WRMPs), released by water companies in England and Wales in 2008. They found that climate change had the largest effect on potential reductions in supply, with impacts ranging from no reductions in deployable output to more than 50% for the individual resource zones assessed. Climate change significantly reduced the deployable output of 44 out of the 68 resource zones, with 35 suffering severe impacts. Clearly, understanding trends in future spring-summer potential recharge from crop fields as a complement to groundwater recharge from other areas is important for adaptive and proactive groundwater management.

For six regions (EE, EM, NEE, SEE, WM, and YH) in the current study, future reductions in potential recharge over baselines were consistent for the time slices and emissions scenarios. Given that agriculture has the largest share of UK land area and cereals having the largest share of cultivated land area, the results of the current study has direct implications for land use and agricultural land management in relation to groundwater resources management in the UK. Particularly, the conversion of crop fields to other uses and land management practices that lower potential recharge in England should be discouraged. In regions with large reductions in potential recharge, arable crop fields could be maintained to augment groundwater recharge while improving infiltration. Here, planned and controlled withdrawal is necessary while alternative supplies or mitigating measures are sought to balance expected increase in demand. Water managers can work with agronomists to identify and improve infiltration in areas that can contribute substantially to potential recharge. For regions where maintenance of base flow is becoming a challenge, it would be important to put even more controls on groundwater depletion in the spring-summer period in the future to help maintain or improve water levels (Crosbie et al., 2013).

In the current study, Wales recorded increases in potential recharge over baseline values, indicating a potential to reduce the water stresses in Wales. In the regions that consistently recorded increase in potential recharge over the time slices and emission scenarios, drainage systems might be necessary to reduce the magnitude or duration of soil saturation, potentially mitigate flood risks (for example in Scottish regions) and maintain crop production. It should be noted, however, that this study assessed the future contribution to potential groundwater recharge from spring barley crop fields in the fourteen UK administrative regions. It did not assess actual groundwater storage, which takes much longer time to build up. Proportion of potential recharge that contributes to actual storage might also vary due to losses. This study did not consider topographic effects and changes in soil management practices which can influence the spatial and temporal

magnitude of potential recharge.

## 6. Assumptions and limitations

Studies on the effects of projected climate change on potential groundwater recharge often have large uncertainties and are further limited by the underlying assumptions. In the current study, potential recharge from barley crop fields under projected climate change was investigated. Based on the circumstances at the time of the study, several assumptions were made that limit the study. Each region was represented with the same soil type and crop. Spatially, soils vary considerably over short distances and, at coarse scale, a mapping unit will typically contain more than one type of soil. In this study, soil properties were derived as the average properties of soil mapping units (SMU) constituting the dominant soil in a given region according to the SINFO Database (Baruth et al., 2006). Given the importance of soil hydraulic properties for potential recharge, the results in the current study provide an impression of potential direction of change even though the magnitude of change in potential recharge could only be indicative. Spatio-temporal changes in soil properties were not considered and optimal conditions of soil fertility were assumed. Soil fertility can affect crop water use and thereby potential recharge. Artificial drainage was also not considered. A spatially explicit study, with soil data at sub-regional spatial scale, could yield a different result. Next, several spring barley genotypes or varieties are grown within each UK region. These genotypes or varieties, even though could have similar water use under adequate soil water supply (Yawson, 2013), would have different water use and therefore different effects on potential recharge under projected climates. However, it was important to use one genotype (Westminster) as a test or representative crop to make the study less complicated. Finally, the current study considered only potential recharge within the barley crop season from spring to summer under the projected climates. It is recognized that winter recharge is crucial for groundwater. However, due to projected conditions during summer periods, it is important to have an indication of the magnitude and direction of change in potential recharge from sowing time in spring when the soils are at field capacity to harvest in summer. Simulating the effect of climate change on potential recharge from barley crop fields in both winter and spring would have required much more parameters (e.g. pre-sowing and postharvest field management parameters between winter and spring), complication, and work than circumstances could permit. Based on these limitations, the results in the current study are applicable to spring-sown barley crop fields, with genotype Westminster, and on the representative soil types used.

## 7. Conclusions

The UK is projected to have hotter and drier summer conditions, with adverse implications for summer flows in England and Wales. In the UK, groundwater crucially supports public water supply, agricultural and industrial water uses, especially in England and Wales where water stresses during summer is a major concern. Crop fields contribute to potential recharge (water that drains or percolates from the unsaturated root zone to the underlying saturated zone). To contribute to understanding of the effect of projected climate change on potential recharge from crop fields and to support adaptive management responses with regards to groundwater resources and agronomic practices, this study assessed the contribution of spring barley crop fields to potential groundwater recharge under projected climate change in the fourteen administrative regions of the UK. The results show regional variations in potential groundwater recharge under the three emissions scenarios and time slices considered. The results show that Southwest Scotland (SWS), Northwest Scotland (NWS), Northern Ireland (NI), and Wales (WA) will have large increases in potential recharge from spring barley crop fields, while Eastern England (EE), East Midlands (EM), Northeast England (NEE), Southeast England

(SEE), West Midlands (WM) and Yorkshire and Humber (YH) would have the largest reductions in potential recharge. Largely, the reductions or increases in potential recharge over baseline values were consistent across the time slices for each emission scenario, indicating less uncertainty across the time slices. Higher and less variable crop evapotranspiration was a major driver of the observed reductions in potential recharge. Within the limits of the current study, the results provide an indication of the direction of changes in potential recharge from spring barley crop fields. Practically, the results indicate potential changes that can be introduced in the groundwater recharge regime as a result of changing potential recharge from crop fields. While water demand and abstraction could be high during summer, the results show that in some regions, diffuse potential recharge from crop fields will reduce due mainly to higher rates of evapotranspiration. This has implication for the planning and management of groundwater abstraction or depletion and measures to augment groundwater resources to respond to potentially higher demands. For the regions that showed large increases in future potential recharge, adaptive agronomic management

responses would include consideration of drainage to avoid excessive and or prolonged soil saturation. Overall, the results indicate possible alterations in future groundwater recharge due to direct effects of changes in crop evapotranspiration rates and rainfall on potential recharge from spring barley crop fields in the UK. Further studies are required to fully quantify the effect of these changes on potential recharge throughout the year, incorporating both spring and winter barley.

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## Appendix A

### a. Crop parameter values for barley genotype Westminster used for the simulations

Symbol	Parameter description	Value
<b>1. Crop Phenology</b>		
<b>1.1 Development of green canopy cover (CC)</b>		
CC <sub>0</sub>	Initial canopy cover (%)	3.6
	Time from sowing to emergence (days)	15
CGC	Canopy growth coefficient (fraction per day, % day <sup>-1</sup> )	10
CC <sub>x</sub>	Maximum canopy cover (%)	85
CDC	Canopy decline coefficient (fraction per day, % day <sup>-1</sup> )	8
<b>1.2 Development of root zone</b>		
Zn	Minimum effective rooting depth (m)	0.30
Zx	Maximum effective rooting depth (m)	0.70
	Shape factor describing root zone expansion	1.5
<b>2. Crop Transpiration</b>		
KC <sub>Tr,x</sub>	Crop coefficient at maximum CC	1.15
	Decline of crop coefficient (% day <sup>-1</sup> ) due to ageing	0.15
	Effect of canopy shelter on surface evaporation in late season stage (%)	50
<b>3. Biomass production and yield formation</b>		
<b>3.1 Crop water productivity</b>		
WP*	Water productivity normalized for ET <sub>0</sub> and CO <sub>2</sub> (g m <sup>-2</sup> )	15
	Water productivity normalized for ET <sub>0</sub> and CO <sub>2</sub> during yield formation (as % WP* before yield formation)	100
<b>3.2 Harvest index</b>		
HI <sub>0</sub>	Reference harvest index	0.49
	Upper threshold for water stress during flowering on HI	0.82
	Possible increase (%) of HI due to water stress before flowering	12 (strong)
	Coefficient describing positive effect of restricted vegetative growth during yield formation on HI	Moderate
	Coefficient describing negative effect of stomatal closure during yield formation on HI	Moderate
	Excess of potential fruits	Moderate
	Allowable maximum increase (%) of specified HI	15
<b>4. Stresses</b>		
<b>4.1 Soil water stress</b>		
P <sub>exp,lower</sub>	Lower threshold of water stress for triggering inhibited canopy expansion	0.60
P <sub>exp,upper</sub>	Upper threshold for canopy expansion (canopy expansion ceases)	0.27
	Shape factor for water stress coefficient for canopy expansion	3.5
P <sub>sto</sub>	Upper threshold for stomata closure	0.60
	Shape factor for water stress coefficient for stomatal control	3.0
P <sub>sen</sub>	Upper threshold for early senescence due to water stress	0.60
	Shape factor for water stress coefficient for canopy senescence	3.5
P <sub>pol</sub>	Upper threshold of soil water depletion for failure of pollination	0.80
	vol% at anaerobic point (with reference to saturation)	15

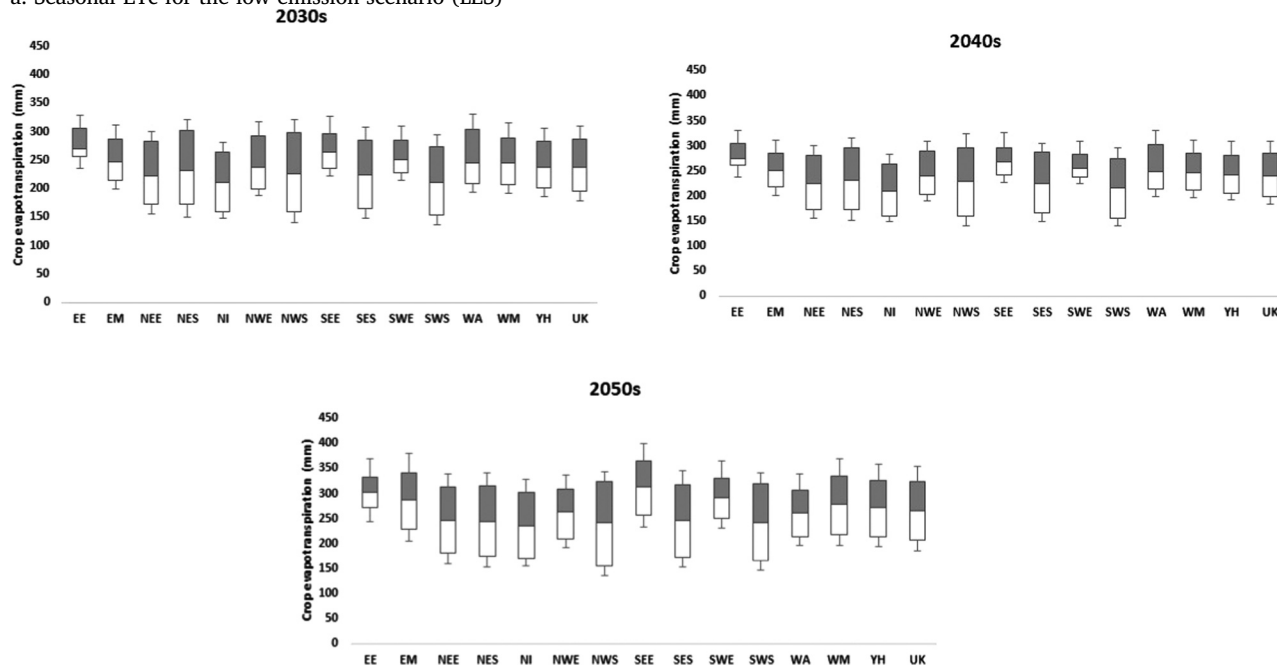
### b. Crop parameters for simulations in growing degree days

Symbol	Description	Value
<b>Threshold air temperatures</b>		
T <sub>base</sub>	Base temperature (°C)	0
T <sub>upper</sub>	Upper temperature (°C)	18

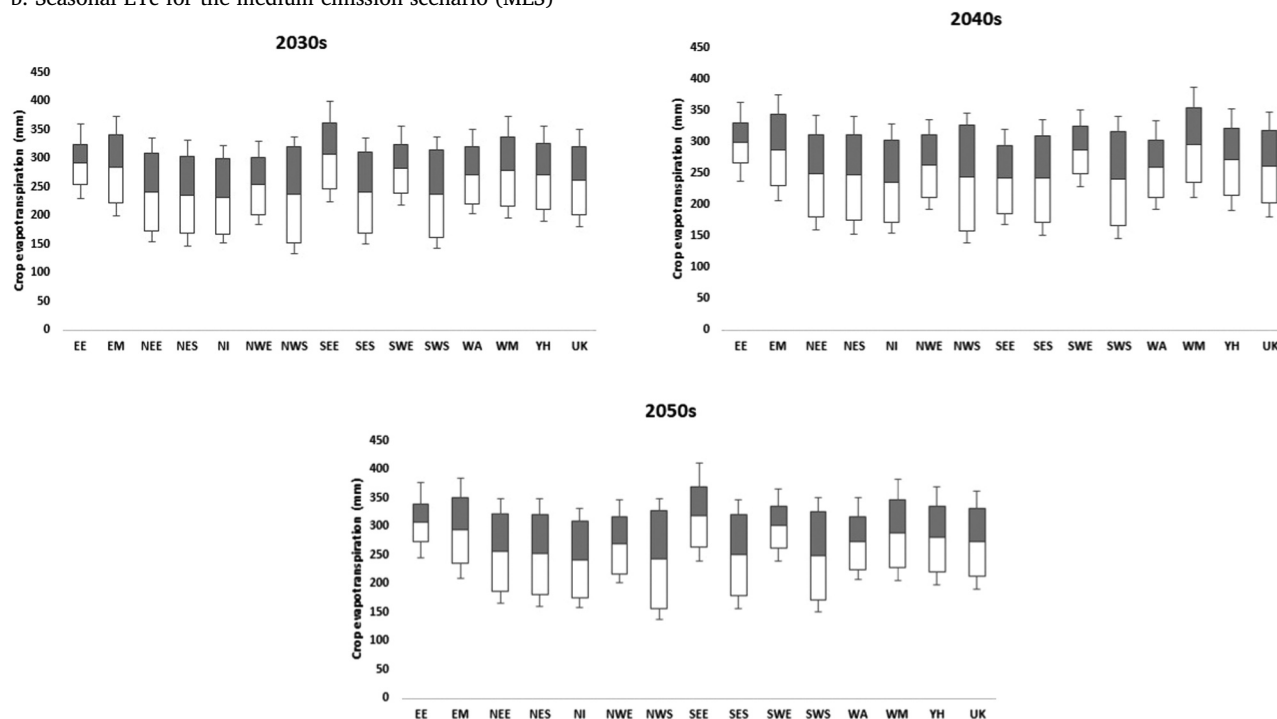
<b>Development of green canopy cover</b>		
	Time from sowing to emergence (GDD)	135
CGC	Canopy growth coefficient (fraction per GDD)	0.813
	Time from sowing to start senescence (GDD)	1315
CDC	Canopy decline coefficient (fraction per GDD)	0.602
	Time from sowing to maturity	1675
<b>Flowering</b>		
	Time from sowing to flowering (GDD)	950
	Length of flowering stage (GDD)	215
<b>Air temperature stress</b>		
	Minimum air temperature below which pollination starts to fail (cold stress, °C)	5
	Maximum air temperature above which pollination starts to fail (heat stress, °C)	30
	Minimum growing degrees required for full biomass production (°C - day)	15

## Appendix B. Seasonal crop evapotranspiration (ETc)

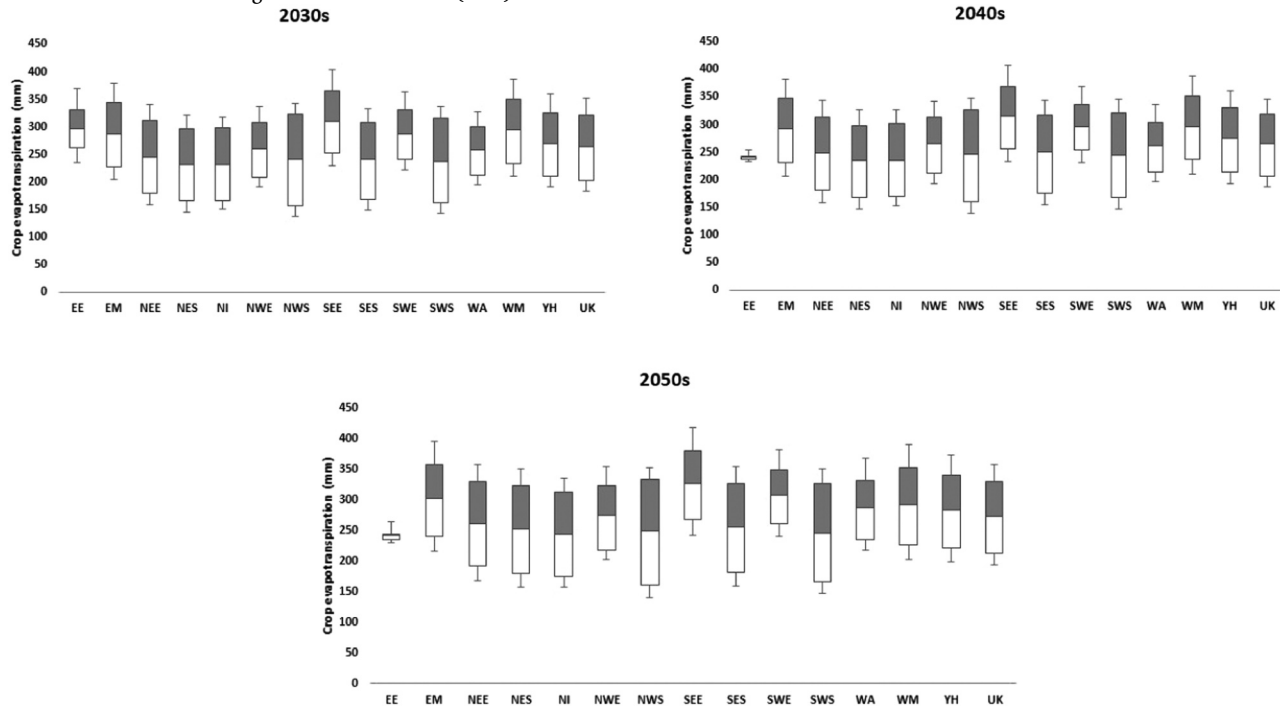
### a. Seasonal ETc for the low emission scenario (LES)



### b. Seasonal ETc for the medium emission scenario (MES)



## c. Seasonal ETC for the high emission scenario (HES)



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